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Drying Speed Testing of PES Fabric with Defined Moisture Management

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Abstract
This paper deals with the evaluation of the moisture management of woven polyester fabric in three basic weaves – plain, twill and satin. It details types of liquid management and evaluates fabric comfort in terms of liquid moisture transport, drying speed and the moisture management of resistivity. It discusses the relationship between moisture management and the drying time of textile structures. New equipment is defined for drying speed determination, and its schematic and principles are discussed in this paper. Because the methods have some limitations and matters of presumption, the necessary interpretation of results is also discussed.

Key words: *moisture management, drying rates, hydrostatic resistance, woven fabrics.*

Introduction

We often encounter the concept of fast-drying clothes. The majority of apparel producers label clothes and final products with this term for textiles made from synthetic fibres which have got a lower wettability in comparison to natural fibres. Testing is a necessary instrument for the exact determination of newly invented types and constructions of fabrics, as well as for the profiles of fibres. Unfortunately, existing methods do not provide a sufficient manual on how to test the drying speed objectively. The important factors mostly neglected are the influences of flow speed or the heating of human skin.

This paper summarises important standards dealing with moisture management and determines a way of textile testing (***Figure 1***).

Related standard AATCC Test Method 195-2009: The Liquid Moisture Management Properties of Textile Fabrics are based on a kind of wetting resistivity in relation to textile geometry and fabric parameters when the sample is placed between two electronic sensors to make it possible to apply liquid in the middle of the sample. Electrical resistance is detected in a dynamic way for the process in the plane of both surfaces and through the material [2]. More studies were performed to determine the moisture management of textiles, for example [3].

The basic dynamics of capillary action can be described with the Lucas–Washburn ***Equation (1)***. Capillarity is based on the balance of the intersurface and gravity forces of the liquid between the fibers. The Lucas–Washburn equation is derived from the relation of fluid in a tube named the Hagen–Poisseuill law ***Equation (2)***. For more see [1, 4].

$$\frac{dH}{dt} = \frac{R*\rho*g*(2\sigma_{LG}*\cos\theta - H*R)}{8*H*\eta} \quad (1)$$

$$\frac{dV}{dt} = \frac{\pi(p_1 - p_2)r_k^4}{8h_k\mu} \quad (2)$$

The presumption for the use of this model is the necessity of a parallel capillary, which is not possible to find in most fabrics. Important inputs are the angle between the water and the fiber, the surface tension and the geometry of pores. Neglected are fiber swelling, the change in surface energy with time, the water surface height in the vertical dimension in the fabric, and the dimension of pores, which change their diameter as fibers deform in the fabric. For the combination of relations ***Equations (3)*** and ***(4)*** go to [4, 5].

$$\frac{dH}{dt} = \frac{R^2\rho g\,(Hmax - H)}{8H\eta} \quad (3)$$

For analytical determination of the previous equation it is possible to use the following version with a square root aproximation ***Equation (4)***. For more see [1,4].

$$H = \frac{\rho R^2 g H_{max}}{8\eta}\sqrt{t} \quad (4)$$

Where, H is the max suction, m, H_{max} the maximum balanced suction, m, t the time, s, R the capillary radius, m, ρ the liquid density, kg.m^{-3}, g the gravitational acceleration, 9.81 m.s^{-2}, σ_{LG} the intersurface force in the liquid, N.m^{-1}, Θ the contact angle between the liquid and fiber, °, η the dynamic viscosity of the liquid, kg.s^{-1}.m^{-1}, V the liquid volume, m^3, r_k,h_k the radius and height of the tube, m, and p_1-p_2 is the difference in pressure at the two ends of the tube [1, 4].

Although it is possible to use the same principles for determination of the suction in a capilary and in wovens fabrics, the distribution of liquid in a fabric is more complex due to its shape and curved surface. Suction in fabrics occurs not only between yarns but also in them .It is possible to predict that in the bottom part of the fabric a greater quantity of liquid will be present than in the upper part [1, 4].

The capillary effect greatly influences the suction of material, as defined above, and describes our moisture management part of the experiment. The capillary effect is important for the absorptivity of textiles,

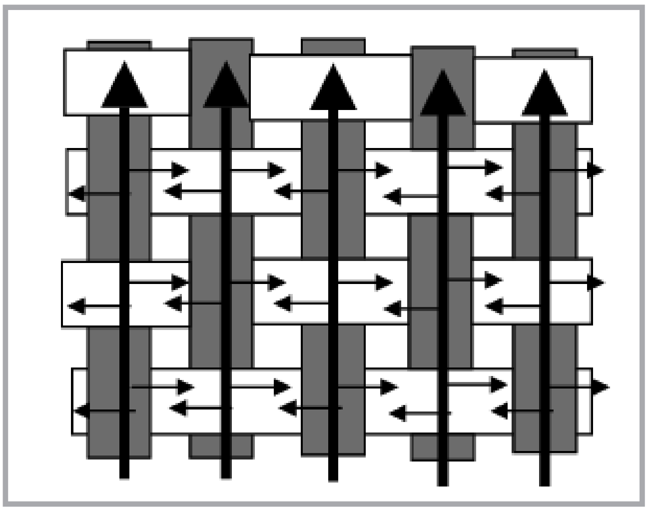

Figure 1. *Transport of liquid in textiles during suction – a net model where arrows represent the main fluid of humidity including side branches [1].*

which is the initial state for drying. In the end phase of moisture management, drying begins. Nevertheless, the speed of humidity decreases from the free water surface in the drying process.

Drying is a process during which liquid (water) is removed from the wetted fabric. First, water evaporates from the free level on the fabric surface and transferred away by the convection flow and lateral gradient of humidity created inside the fabric, which drives water from inside the fabric to its surface (internal diffusion) [5].

The wet material is therefore a mixture of absolute dry solids and water [5]. The dimensionless fraction of moisture in the fabric W_w is expressed by ***Equation (5)***:

$$W_W = \frac{m_w}{m_F} \qquad (5)$$

Where, m_W is the mass of water, kg and m_F that of dry fabric, kg [5].

Moisture can take the form of free moisture, which can be removed under certain conditions, and irremovable moisture, which remains in the material after drying and is in equilibrium with the water content in the air. This equilibrium state also depends on the size of the dried material [5].

Industrial drying systems and some testing instruments use non- isothermal drying, where along with mass transfer, convection heat transfer also takes place. The speed of this process expresses the intensity of moisture mass flow (drying rate) m^*, kg.m^{-2}.s^{-1}.

$$m^* = \frac{\partial^2 m_w}{\partial S \partial \tau} \qquad (6)$$

Where, m_W, kg, represents the mass of water, S, m^2, the area, and τ, s, is the time. The driving force here is the difference in water vapour concentration or the difference in water vapour partial pressures [5].

At the beginning of the process, the moist material is placed in contact with an air stream of the same or higher temperature than that of the material and exhibiting a lower concentration of moisture than that on the surface of the drying material [5].

The drying process can be divided into three parts [5, 6]:

I. Initial drying period – this phase lasts a very short time and instruments do not record it. The material starts to warm up to the temperature of a wet thermometer.
II. Period of a constant drying rate of the material – this is the most important phase of the drying process, characterising the thermo-physiological comfort of a person wearing a dress during highly physical activities. Here, the level of the drying rate can be easily determined by means of the convection mass transfer coefficient ß in dependence on the dimensionless numbers (Sherwood and Schmidt [7]).
III. The period of a decreasing drying rate – the period of evaporation of moisture from the inside of the material. This part of the drying procedure sometimes lasts a long time when drying fabric containing hydrophylic fibres. The process of heat and mass transfer stops when the material cannot be dried more under the given environment conditions [6].

Methods describing the drying process and allowing to define the speed are as follows: Nonofficial techniques were already published in 2008 as a technical attachment of AATCC/ASTM for textile goods. The official standard [8] AATCC Test Method 199-2011: Drying Time of Textiles: Moisture Analyser Method was published later on. This testing method is based on the gravimetric principle when wetting is defined. The wetting of a sample is absorption in deionised water for 1 minute. The decrease in weight is detected in real time conditions. The end state of the measurement is when the weight of the sample is only 4% higher than in a completely dry state. The method is limited for highly absorbent materials, such as the first layer of sports clothes for longer than 30 s [9] and is suitable for suction materials according to the definition in (AATCC TM 79 – suction of textiles).

The important BMI method (from a set of standards from 2015 – TNI CEN/TR 16422: The buffering capacity of liquid sweat and sweat transport) uses a small skin model to evaluate water vapour resistance and thermal resistance. The skin heat temperature and airflow are test parameters on the instruments following ISO 11092 [10]. An advantage of this method is the simulation of human skin with a wet polyester fabric which has absorbed 15 cm^3 of humidity at a temperature of 35 °C. Testing lasts 15 minutes, and the difference is detected by the gravimetric method, which is not sensitive to the drying process or the state of the dry material [11].

The standard for the exact value of the moisture drying rate with drying characteristics is ISO 17616: Textiles: Determination of the moisture drying rate, and is also useful for determining the speed of drying of the textile. It is also based on the gravimetric principle in a stationary state of air without a heating effect. Testing lasts 60 minutes or at least to 10% of the initial humidity weight [12]. The same principle is used in Asian countries in JIS L 1096: 1999 – Drying speed [13].

In 2004 a collection of authors – SOUSA, L.H.C.D. et al. [14] published a study that presents an analysis of the impact of some process variables through the convective and conductive-convective drying of natural textile fabrics. Two types of drying equipment are used for their analysis. The first technique consists of

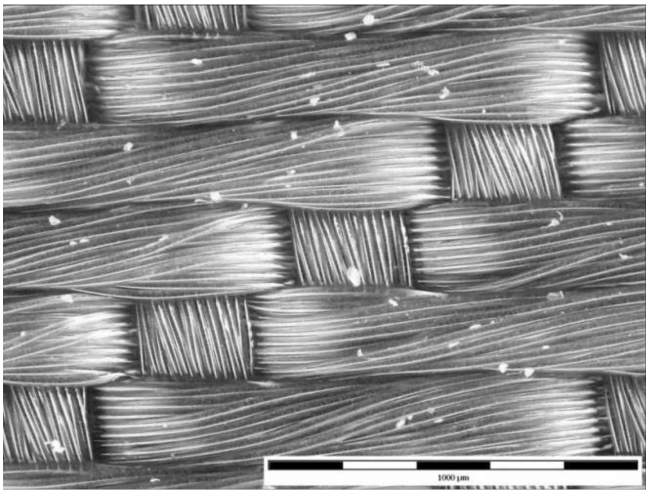

***Figure 2.** Microphotography of the sample tested, twill weave of multifilament yarns, magnification 10x.*

using a drying chamber, which is adapted from a drying module of a general chemical laboratory. Cotton samples are placed inside the drying chamber and are exposed to a convective flow of hot air. The second instrument consists of a metal box heated by a thermostatic bath on which a hot plate is located. On this hot plate a textile sample is placed, and the system is exposed to a forced convection of ambient air through the use of an adjustable fan.

In this study we follow the influence of the initial moisture content of the fabric, drying (by hot air flow and heated surface), temperature and air flow speed on the behaviour of curves during operating conditions. Unfortunately, in this case the type of flow is not defined. Details of the experimental equipment and the construction of drying curves can be found in the Sousa study [15].

This document studies the applicability of generalised drying curves in the convective and conductive/convective drying of cotton fabrics and the usability of Page ***Equations (1)***, ***(2)*** & ***(3)*** for the modelling of drying curves published in the Motta Lima, O. C. study [16].

$$Y = e^{\left(-K\cdot t_{Ad}^{n}\right)} \tag{7}$$

$$Y = \frac{X}{X_0} \tag{8}$$

$$t_{Ad} = \frac{Nc\cdot t}{X_0} \tag{9}$$

Where, Y [–] denotes the dimensionless moisture content (= X/X0) , X0 [–] the initial moisture content dry basis, X [–] the moisture content dry basis, K [–] the dry constant, t_{Ad} [–] the dimensionless drying time, NC the constant rate of drying and [1/s] a n [–] the dimensionless parameter.

The Sousa article relates to the previous studies of Günther et al. and Brunello et al. [17, 18], who studied the behaviour of the fixed bed drying of cellulose pulp at different operational conditions. In this study, it was verified that the initial moisture content of samples has no effect on the the initial rate of drying. Brunello et al. [18] analysed and proposed a set of equations to correlate the effects of temperature and speed on the initial drying rate.

Krasnikov [19] and Ciesielczyk [20] initiated a discussion about methods of creating generalised drying curves based on the regularity of moisture transfer during drying processes. Based on that, Ciesielczyk proposed a universal drying curve relating the same dimensionless moisture (X/X0) to the dimensionless time, defined from the first period of a constant drying rate, the time, and X0. It was tested on the basis of experimental results of ammonium sulfate, gel silica and sand drying in a batch-fluidised drier.

After one year a study [21] was performed which deals with the influence of thermal transport on moisture management and describes models which represent textile behaviour during drying. The experimental part of that paper deals with the convective drying of wool and on the basis of experimental data compares the Lewis model and a new more accurate model to use in the wool industry. It summarises a particular period of drying.

Also, in recent years many studies have been published, in which measurements are analysed according to the available standards. For example Mrs. Laing's study [22] "Determining the Drying Time of Apparel Fabrics" deals with two methods of evaluation of the drying time. The first method is based on the standard AATCC Test Method 195-2009 without air flow speed. The second method is based on the BPI method with the principle of a wet sample facing right side up at a 90° angle to an air flow speed of 1 ± 0.05 m.s^{-1} and in contact with a heated plate (according to the standard ISO 11092 [10]).The stable state and the end of measurement are defined when the temperature is stabilised at 35 ± 0.1°C. This way is the best of existing methods because it respects real conditions; but it still does not detect the whole drying process.

Description of the experiment

The experimental material is defined first by its moisture management properties with a set of methods, such as the capillary action test, the Moisture Management Test using an MMT SDL Atlas instrument, and the droplet test. After the determination of moisture management, it is possible to define the reverse process – drying, especially for samples with good moisture management or ones with very good humidity transport through the thickness of the sample. Such a material can be defined as fast-drying, and complex drying characteristics including skin heating and air flow in the time are necessary to be determined.

The importance of humidity absorption was not affected by the fibre cross sec-

***Table 1.** Material identification for a set of PES fabrics.*

Weave	Plain					Twill (3/1)					Satin (7/1)				
Weft set, 1/cm	21	23	25	27	29	25	27	29	31	33	29	31	33	35	37
Area density, g/m^2	80	79	95	94	96	95	96	95	105	108	101	103	106	109	118
Porosity, %	47.4	45.8	44.2	42.6	41.0	44.2	42.6	41.0	39.4	37.8	41.0	39.4	37.8	36.2	34.6

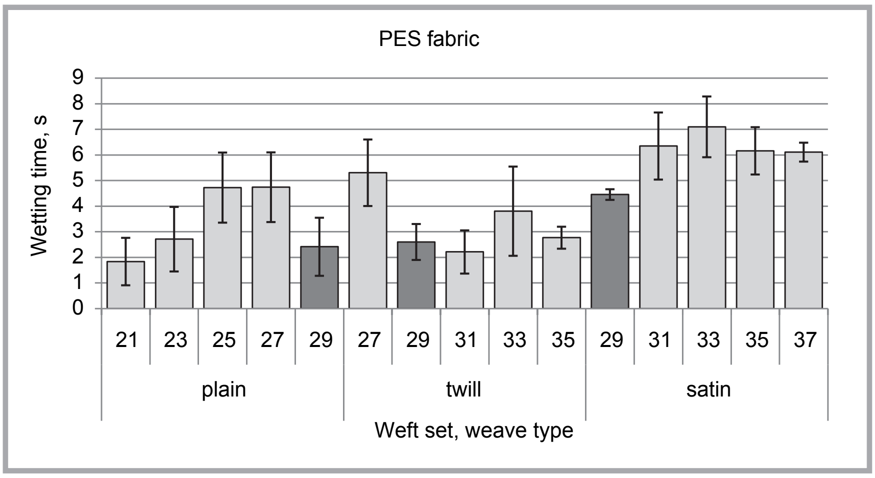

Figure 3. Wetting time (in seconds) for samples in all weaves with a focus on the weft set of 29 yarns per cm.

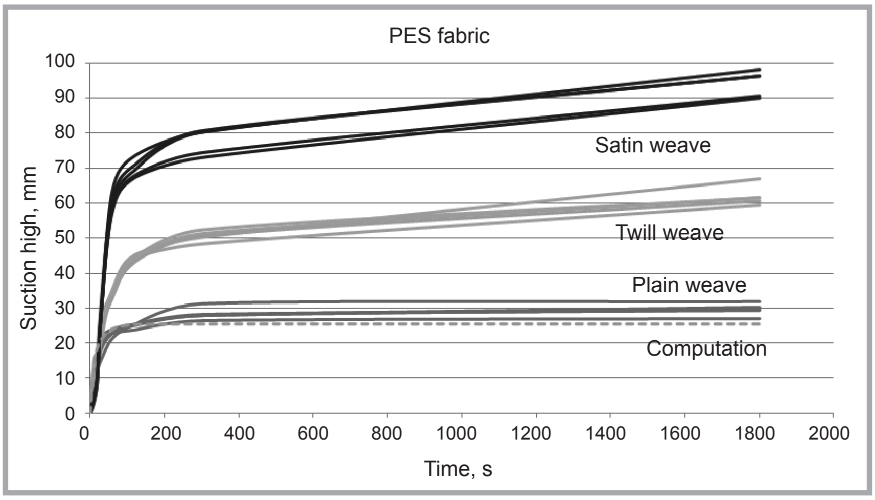

Figure 4. Suction maximum in relation to time for PES fabric with a visible difference in weaves and warp direction.

tion of polyester material in source [23], where they studied the dependency of circular and four lobar cross section fibres. Therefore we chose simple circular fibres for our experiment. Therefore we chose simple circular fibres for our experiment and did not include various profiles of polyester fabrics in this study. Previous studies concluded that the shape of the fibre does not affect the initial absorbance; only wicking in terms of kinetic absorption in the structure.

Materials

A number of samples of PES fibres in plain, twill and satin weaves, provided by the Department of Textile Technologies FT TUL, were tested. PES material was chosen as an abstract in plain, twill (3/1) and satin (7/1) weaves, with the warp set at 42 [1/cm], fineness of warp yarn of 78 dtex, and fineness of weft yarn of 165 dtex (***Figure 2, Table 1***).

Results and discussion

Suction and moisture management were tested, including their theoretical computation based on the model of the Lucas–Washburn ***Equations (1)*** and ***(4)***. Plain and twill fabrics do not show a significant difference in the wetting time, and the average for all samples is around three seconds. On the other hand, the satin weave once more shows the wetting time to be longer by around six seconds, and the difference between the two other weaves is statistically significant. The drying speed was tested in three fabrics from a set of tested fabrics with the same parameters in the yarn set. Those fabrics are highlighted in dark grey in ***Figure 3***.

A linear model was used, and the independent variable in the Lucas–Washburn Equation was the theoretical suction. As is visible from ***Figure 4***, the closest prediction is presented by the plain weave, where the calculation (dashed line) is not sensitive to the fabric weave in this case.

The distance from the droplet to the maximum wetted radius is dependent on the weave structure, and in our case definitely, as is visible from the results measured on the moisture management tester – SDL Atlas, ***Figures 5, 6*** and ***7***. Samples were tested for droplet spreading in the woven structure for 120 seconds, where the first 20 seconds was liquid application. The Figures help to visualise maximum water location at the end of the test. Visualised samples are in the same weft set, describing the inner side of the material on the left side and outer on the right. Plain weave is symmetrical, and the management of liquid is same on both sides. Twill material shows higher concentration on the outer side when the float sections transport liquid faster in the closer radius than for plain weave. Our satin fabrics transported liquid the fastest for all samples, even on both sides. The management of these samples is extraordinary good in the 120 seconds tested for the reason that floats are long in the weave (7/1).

Different moisture management was confirmed for various woven structures, but calculation according to the Lucas-Washburn Equation is effective for prediction only for plain weave. After liquid absorption by the sample, drying starts, and we constructed new equipment for testing it effectively.

The drying properties of woven PES were tested on a prototype instrument, which is constructed from two main parts, see ***Figure 8***, inspired by the Permetest described in [24, 25]. In the so-called channel, different speeds of laminar flow blown over the fabric tested can be adjusted. And the second part is the measuring unit, on which the fabric tested is horizontally positioned. The measuring unit consists of analytical scales, aluminium ribs and plates. The aluminium rib with a plate attached is blown by the other ventilators, which provide isothermal drying conditions. The sample measured is fixed to the plate by the clamping means of the frame. The sample tested extends its entire surface into the channel. The whole device can be placed in a climatic chamber.

The instrument is connected to a PC, where the weight of the sample tested is recorded in minute intervals. Every minute the ventilator is stopped for 7 seconds, and the SW records the current weight of the sample.

Our experiment ran at a temperature of 18 °C and relative humidity of 65%. Samples with the same warp and weft set of 29 [1/cm] were chosen, and their size was 11 x 8 cm. All samples were air-conditioned in a laboratory environment for 24 hours and weighed on the analytical scales of a test instrument in a dry state to define the standard weight of the sample. The samples tested were dipped into distilled water at a temperature of 18 °C for 60 minutes. Every sample was left to drain away on absorbent paper for one minute after that, and placed onto the instrument on the plate. Testing begun after the ventilator achieved a speed of 5 m.s^{-1}. The test parameters were a temperature of 18 °C and relative humidity of 65%. See the drying results on the following graphs.

The maximum absorbed water content is 51% for the satin weave, 35% for the twill and 23% for the plain in a dry state in testing, visualised in ***Figure 9***. It is obvious that the drying curves begin at a different starting point of the absolute water weight in the fabric tested. The suction of PES fibres is small. The sample tested in this example is dependent on the different porosity of samples (the size of macro pores varies in selected weave types). The decrease in humidity has very close trends for all samples.

The graph in ***Figure 10*** shows the drying process in the case of the absolute water content being the same for all samples tested. When fabrics have the same humidity content in the means of plain weave maximum water suction ability, the drying speed does not have an effect

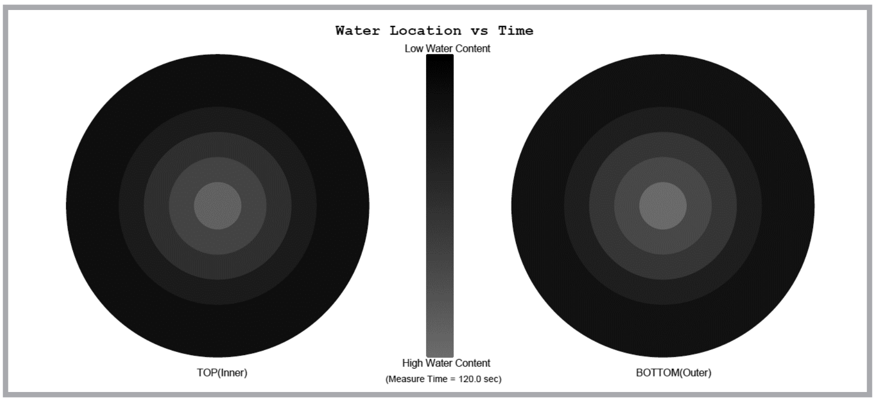

Figure 5. *Maximum Wetted Radius in PES plain fabric, weft set 29.*

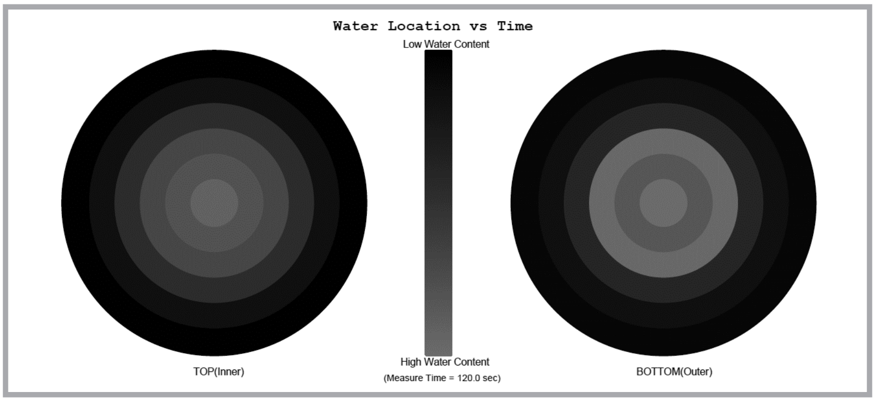

Figure 6. *Maximum Wetted Radius in PES twill fabric, weft set 29.*

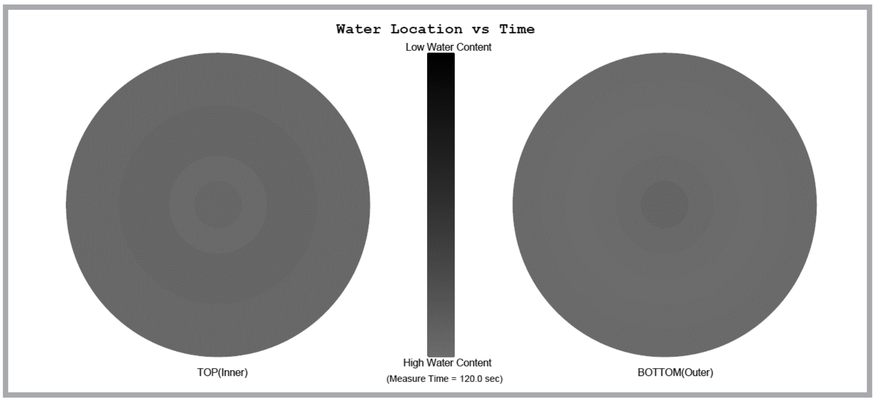

Figure 7. *Maximum Wetted Radius in PES satin fabric, weft set 29.*

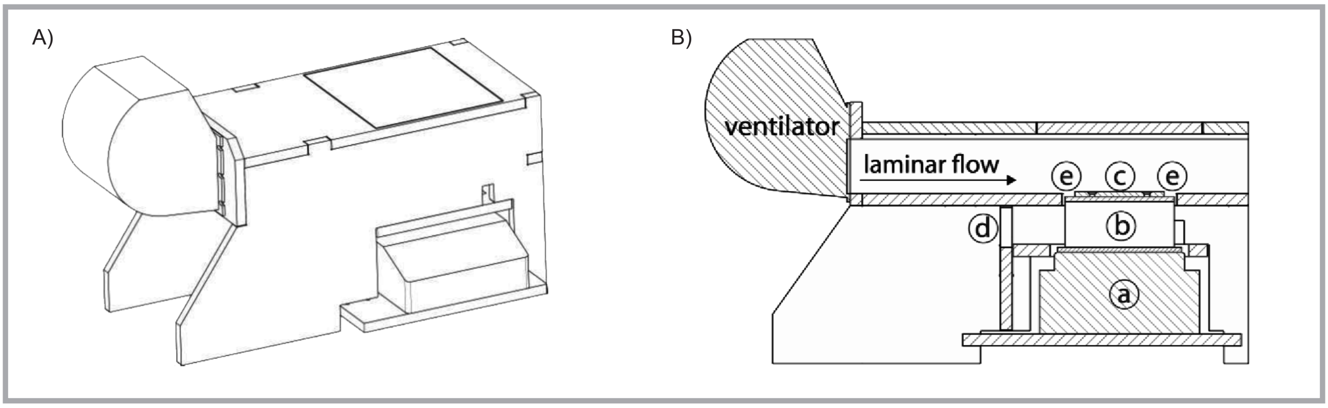

Figure 8. *A) new instrument – isometric view, B) new instrument – sectional view (analytical scales (a), aluminium ribs (b), plates (c), 3 ventilators (d), clamping means of the frame (e).*

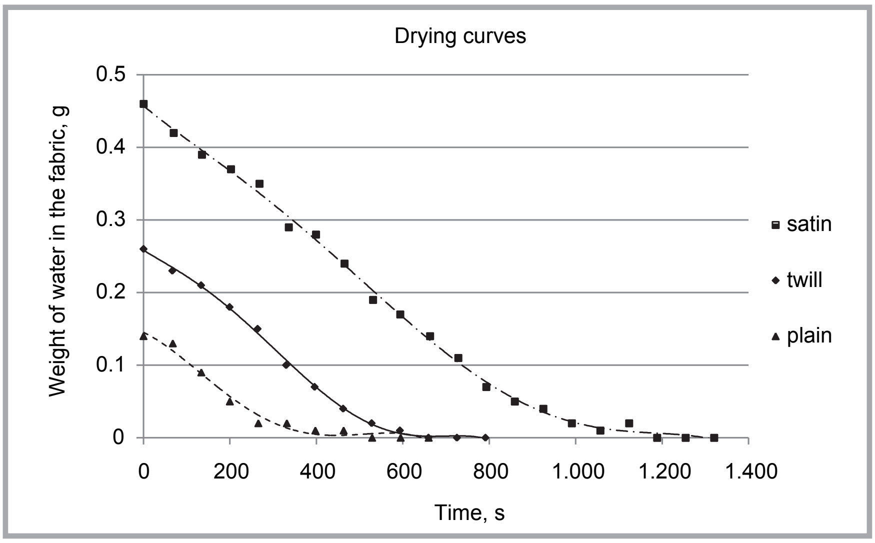

***Figure 9.** Drying curves for maximum water content (suction ability of samples).*

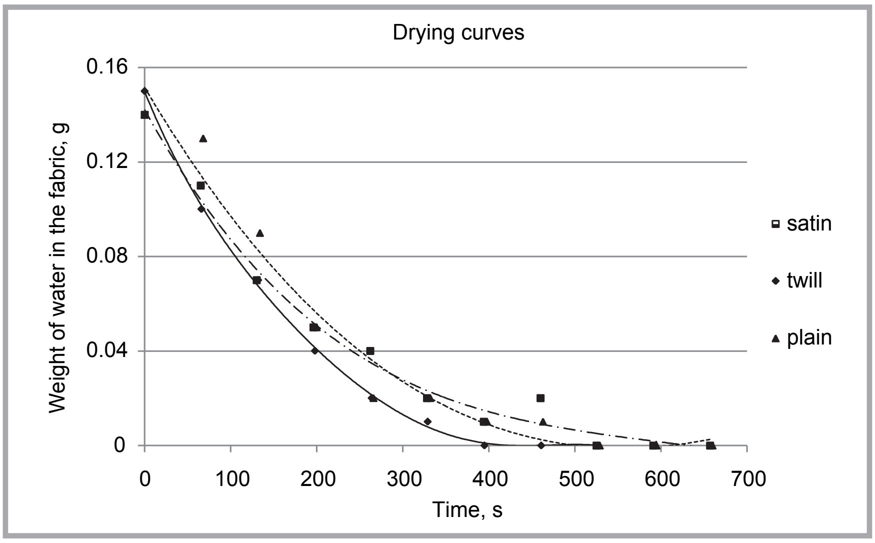

***Figure 10.** Drying curves for the same level of absolute water content of samples.*

on the weave type as in the previous test. The drying curves are very close together.

Conclusions

Changes in moisture management transport can be seen in terms of the weave of fabrics. The correlation of the suction high test is mostly dependent on the warp direction. Satin weave samples show a significant difference to twill weave and plain weave in time. Plain weave as a structure with the highest curvature in its structure and tightness between yarns shows the smallest suction and moisture management. On the other hand, satin weave, with its float, has got high suction in the warp direction – the flotation affected the moisture management. Straight passages of satin float parts support the capillarity effect, thus moisture is highly spread in satin weave. After the detection of the drying time, it will be possible to define the relationship with fabric parameters, for example the suction high in the time range.

Although the results are not that clear in the reverse process, the drying speed and the trend in humidity decrease are very close together for various weaves from this very first testing with a new instrument. The test proved that what was tested and the results are important for our next steps, which will be testing at various air velocities, with a broad sample set, in various environmental conditions etc. The new instrument is precise in testing, clear in data interpretation, and relevant to continue with.

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